# NEW CONSTRAINTS ON WIMPS FROM THE CANFRANC IGEX DARK MATTER SEARCH

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**Abstract**

The IGEX Collaboration enriched $^{76}$Ge double-beta decay detectors are currently operating in the Canfranc Underground Laboratory with an overburden of 2450 m.w.e. A recent upgrade has made it possible to use them in a search for WIMPs. A new exclusion plot, $\sigma$(m), has been derived for WIMP-nucleon spin-independent interaction. To obtain this result, 30 days of data from one IGEX detector, which has an energy threshold $E_{thr} \sim 4$ keV, have been considered. These data improve the exclusion limits derived from other germanium diode experiments in the ∼50 GeV DAMA region, and show that with a moderate improvement of the background below 10 keV, the DAMA region may be tested with an additional 1 kg-year of exposure.

## 1 Introduction

Substantial evidence exists suggesting most matter in the universe is dark, and there are compelling reasons to believe it consists mainly of non-baryonic particles. Among these candidates, Weakly Interacting Massive and neutral Particles (WIMPs) are among the front runners. The lightest stable particles of supersymmetric theories, like the neutralino, describe a particular class of WIMPs[1].

Direct detection techniques rely on measurement of WIMP elastic scattering off target nuclei in a suitable detector[2]. Slow moving ($\sim 300$ km/s) and heavy ($10 - 10^3$ GeV) galactic halo WIMPs could make a Ge nucleus recoil with a few keV, at a rate which depends on the type of WIMP and interaction. Only about 1/4 of this energy is visible in the detector. Because of the low interaction rate and the small energy deposition, the direct search for particle dark matter through scattering by nuclear targets requires ultralow background detectors with very low energy thresholds.

To detect the possible presence of WIMPs, the predicted event rate is compared with the observed spectrum. If this predicted event rate is larger than the measured one, the particle under consideration can be ruled out as a dark matter component. Such absence of WIMPs can be expressed as a contour line, $\sigma$(m), on the WIMP-nucleus elastic scattering cross-section plane. This excludes, for each mass, those particles whose cross-section lies above the contour line, $\sigma$(m).

This direct comparison of the expected signal with the observed background spectrum can only exclude or constrain the cross-section in terms of exclusion plots of $\sigma$(m). A convincing proof of the detection of dark matter would require finding unique signatures in the data, characteristic of the WIMP, which cannot be attributed to the background or instrumental artifacts. An example is the predicted summer-winter asymmetry [3] in the WIMP signal rate due to the periodicity of the relative Earth-halo motion resulting from the Earth's rotation around the Sun.

Germanium detectors used for double-beta decay searches have reached one of the lowest background levels of any type of detector and have a reasonable quenching factor ($\sim 0.25$). Thus, with sufficiently low energy thresholds, they are attractive devices for dark matter searches.

Germanium diodes dedicated to double-beta decay experiments[4-11] were applied to WIMP searches as early as 1987. The exclusion contour based on the best combination of data from these experiments is referred to in this paper as the "combined germanium contour". Only recently has this exclusion plot been surpassed by a sodium iodide experiment[12] (DAMA NaI-0), which uses a statistical pulse-shape discriminated background spectrum.

This paper presents a new germanium detector data limit for the direct detection of non-baryonic particle dark matter in the $\sim$50 GeV DAMA mass region.

# 2 Experiment

The IGEX experiment[13, 14], optimized for detecting $^{76}$Ge double-beta decay, has been described in detail elsewhere. The IGEX detectors are now also being used in the search for WIMPs interacting coherently with germanium nuclei. The COSME detector described below, is also operating in the same shield at Canfranc.

The IGEX detectors were fabricated at Oxford Instruments, Inc., in Oak Ridge, Tennessee. Russian $GeO_2$ powder, isotopically enriched to 86% $^{76}$Ge, was purified, reduced to metal, and zone refined to $\sim 10^{13}$ p-type donor impurities per cubic centimeter by Eagle Picher, Inc., in Quapaw, Oklahoma. The metal was then transported to Oxford Instruments by surface in order to minimize activation by cosmic ray neutrons, where it was further zone refined, grown into crystals, and fabricated into detectors.

The COSME detector was fabricated at Princeton Gamma-Tech, Inc. in Princeton, New Jersey, using naturally abundant germanium. The refinement of newly-mined germanium ore to finished metal for this detector was expedited to minimize production of cosmogenic $^{68}$Ge.

All of the cryostat parts were electroformed using a high purity OFHC copper/$CuSO_4$/$H_2SO_4$ plating system. The solution was continuously filtered to eliminate copper oxide, which causes porosity in the copper. A $Ba(OH)_2$ solution was added to precipitate $BaSO_4$, which is also collected on the filter. Radium in the bath exchanges with the barium on the filter, thus minimizing radium contamination in the cryostat parts. The $CuSO_4$ crystals were purified of thorium by multiple recrystallization.

The IGEX detector used for dark matter searches, designated RG-II, has a mass of $\sim$ 2.2 kg. The active mass of this detector, $\sim$ 2.0 kg, was measured with a collimated source of $^{152}$Eu in the Canfranc Laboratory and is in agreement with the Oxford Instruments efficiency measurements. The full-width at half-maximum (FWHM) energy resolution of RG-II was 2.37 keV at the 1333-keV line of $^{60}$Co. The COSME detector has a mass of 254 g and an active mass of 234 g. The FWHM energy resolution of COSME is 0.43 keV at the 10.37 keV gallium X-ray. Energy calibration and resolution measurements were made every 7–10 days using the lines of $^{22}$Na and $^{60}$Co. Calibration for the low energy region was extrapolated using the X-ray lines of Pb.

For each detector, the first-stage field-effect transistor (FET) is mounted on a Teflon block a few centimeters from the center contact of the germanium crystal. The protective cover of the FET and the glass shell of the feedback resistor have been removed to reduce radioactive background. This first-stage assembly is mounted behind a 2.5-cm-thick cylinder of archaeological lead to further reduce background. Further stages of preamplification are located at the back of the cryostat cross arm, approximately 70 cm from the crystal. The IGEX detectors have preamplifiers modified for the pulse-shape analysis used in the double-beta decay searches.

The detectors shielding is as follows, from inside to outside. The innermost shield consists of 2.5 tons of 2000-year-old archaeological lead forming a 60-cm cube and having $< 9$ mBq/kg of $^{210}$Pb($^{210}$Bi), $< 0.2$ mBq/kg of $^{238}$U, and $< 0.3$ mBq/kg of $^{232}$Th. The detectors fit into precision-machined holes in this central core, which minimizes the empty space around the detectors available to radon. Nitrogen gas, at a rate of 140 l/hour, evaporating from liquid nitrogen, is forced into the detector chambers to create a positive pressure and further minimize radon intrusion. The archaeological lead block is centered in a 1-m cube of 70-year-old low-activity lead($\sim$ 10 tons) having

$\sim 30$ Bq/kg of $^{210}$Pb. A minimum of 15 cm of archaeological lead separates the detectors from the outer lead shield. A 2-mm-thick cadmium sheet surrounds the main lead shield, and two layers of plastic seal this central assembly against radon intrusion. A cosmic muon veto covers the top and sides of the central core, except where the detector Dewars are located. The veto consists of BICRON BC-408 plastic scintillators 5.08 cm $\times$ 50.8 cm $\times$ 101.6 cm with surfaces finished by diamond mill to optimize internal reflection. BC-800 (UVT) light guides on the ends taper to 5.08 cm in diameter over a length of 50.8 cm and are coupled to Hamamatsu R329 photomultiplier tubes. The anticoincidence veto signal is obtained from the logical OR of all photomultiplier tube discriminator outputs. An external polyethylene neutron moderator 20 cm thick (1.5 tons) completes the shield. The entire shield is supported by an iron structure resting on noise-isolation blocks. The experiment is located in a room isolated from the rest of the laboratory and has an overburden of 2450 m.w.e., which reduces the measured muon flux to $2 \times 10^{-7}$cm$^{-2}$s$^{-1}$.

The data acquisition system for the low-energy region used in dark matter searches (referred to as IGEX-DM) is based on standard NIM electronics and is independent from that used for double-beta decay searches (IGEX-2$\beta$). It has been implemented by splitting the normal preamplifier output pulses of each detector and routing them through two Canberra 2020 amplifiers having different shaping times enabling noise rejection[7]. These amplifier outputs are converted using 200 MHz Wilkinson-type Canberra analog-to-digital converters, controlled by a PC through parallel interfaces. For each event, the arrival time (with an accuracy of 100 $\mu$s), the elapsed time since the last veto event (with an accuracy of 20 $\mu$s), and the energy from each ADC are recorded.

# 3 Results

The IGEX-DM results obtained correspond to 30 days of analyzed data (Mt=60 kg-days) from IGEX detector RG-II. Also presented for comparison are earlier results from the COSME detector (COSME-1) [7, 8], as well as recent results obtained in its current set-up (COSME-2)[15, 2].

The detector RG-II features an energy threshold of 4 keV and an energy resolution of 0.8 keV at the 75 keV Pb x-ray line. The background rate recorded was $\sim 0.3$ c/(keV-kg-day) between 4–10 keV, $\sim 0.07$ c/(keV-kg-day) between 10–20 keV, and $\sim 0.05$ c/(keV-kg-day) between 20–40 keV. Fig. 1 shows the RG-II 30-day spectrum; the numerical data are given in Table 1.

The exclusion plots are derived from the recorded spectrum in one-keV bins from 4 keV to 50 keV. As recommended by the Particle Data Group, the predicted signal in an energy bin is required to be less than or equal to the (90% C.L.) upper limit of the (Poisson) recorded counts. The derivation of the interaction rate signal supposes that the WIMPs form an isotropic, isothermal, non-rotating halo of density $\rho = 0.3$ GeV/cm$^3$, have a Maxwellian velocity distribution with $\mathrm{v_{rms}} = 270$ km/s (with an upper cut corresponding to an escape velocity of 650 km/s), and have a relative Earth-halo velocity of $\mathrm{v_r} = 230$ km/s. The cross sections are normalized to the nucleon, assuming a dominant scalar interaction. The Helm parameterization[16] is used for the scalar nucleon form factor, and the quenching factor used is 0.25. The exclusion plots derived from the IGEX-DM (RG-II) and COSME data are shown in Fig. 2. In particular, IGEX results exclude WIMP-nucleon cross-sections above 1.3x$10^{-8}$ nb for masses corresponding to the 50 GeV DAMA region[17]. Also shown is the combined germanium contour, including the last Heidelberg-Moscow data[11] (recalculated from the original energy spectra with the same set of hypotheses and parameters), the DAMA experiment contour plot derived from Pulse Shape Discriminated spectra[12], and the DAMA region corresponding to their reported annual modulation effect[17]. The IGEX-DM exclusion contour improves significantly on that of other germanium experiments for masses corresponding to that of the neutralino tentatively assigned to the DAMA modulation effect[17] and results from using only unmanipulated data.

Data collection is currently in progress with improved background below 20 keV. Based on present IGEX-DM performance and reduction of the background to $\sim 0.1$ c/(keV-kg-day) between 4–10 keV, the complete DAMA region (m=$52^{+10}_{-8}$ GeV, $\sigma^p$=($7.2^{+0.4}_{-0.9}$)x$10^{-9}$ nb) could be tested after an exposure of 1 kg-year, i.e. a few months of operation with two upgraded IGEX detectors.

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| **E (keV)** | **counts** | **E (keV)** | **counts** | **E (keV)** | **counts** |
|---|---|---|---|---|---|
| 4.5 | 44 | 19.5 | 9 | 34.5 | 3 |
| 5.5 | 23 | 20.5 | 5 | 35.5 | 2 |
| 6.5 | 29 | 21.5 | 3 | 36.5 | 1 |
| 7.5 | 17 | 22.5 | 4 | 37.5 | 4 |
| 8.5 | 8 | 23.5 | 4 | 38.5 | 2 |
| 9.5 | 14 | 24.5 | 0 | 39.5 | 3 |
| 10.5 | 12 | 25.5 | 2 | 40.5 | 1 |
| 11.5 | 14 | 26.5 | 1 | 41.5 | 5 |
| 12.5 | 10 | 27.5 | 2 | 42.5 | 0 |
| 13.5 | 5 | 28.5 | 3 | 43.5 | 3 |
| 14.5 | 3 | 29.5 | 1 | 44.5 | 4 |
| 15.5 | 3 | 30.5 | 2 | 45.5 | 3 |
| 16.5 | 10 | 31.5 | 2 | 46.5 | 10 |
| 17.5 | 3 | 32.5 | 3 | 47.5 | 1 |
| 18.5 | 5 | 33.5 | 2 | 48.5 | 2 |

Table 1: Low-energy data from the IGEX RG-II detector (Mt = 60 kg-d).

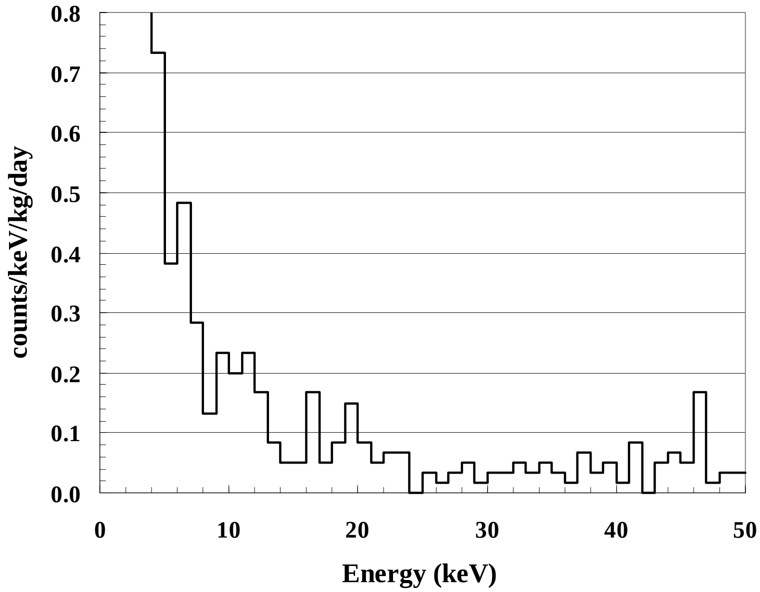


Figure 1: Low-energy spectrum of the IGEX RG-II detector (Mt = 60 kg-d).

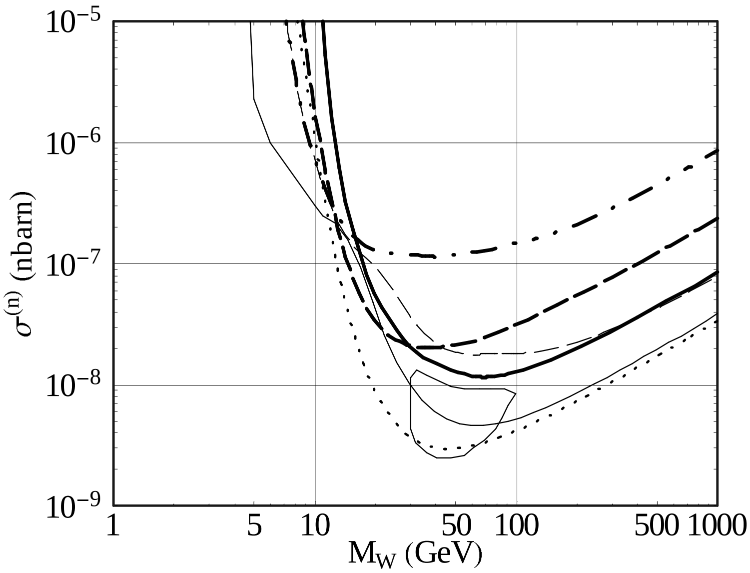


Figure 2: IGEX-DM exclusion plot for spin-independent interaction obtained in this work (thick solid line). Results obtained in other Germanium experiments are also shown: Canfranc COSME-1 data[8] (dot-dashed line), recent COSME-2 data[2, 15] (thick dashed line), and the previous Ge-combined bound (thin dashed line) —including the last Heidelberg-Moscow data[11]. The result of the DAMA NaI-0 experiment [12] (thin solid line) is also shown. The "triangle" area corresponds to the ($3\sigma$) annual modulation effect reported by the DAMA collaboration (including NaI-1,2,3,4 runnings)[17]. The IGEX-DM projection (dotted line) is shown for 1 kg-year of exposure with a background rate of 0.1 c/(keV-kg-day).